Pleiad

Populações Estelares Integradas

Stellar Spectral Libraries

for Stellar Population Studies

SpecModels

http://specmodels.iag.usp.br/

FAPESP

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by **Paula Coelho** for the IAU Symposium 395. 21st Nov 2024, Paraty, Brazil.

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What is a SSL?

SSL = Stellar Spectral Library

A collection of stellar spectra organised in a systematic manner.

- the instrumental parameters (e.g. resolving power and wavelength coverage) are well-defined
- each spectrum is tagged/flagged according to its atmospheric parameters (e.g. spectral type, temperature, surface gravity, chemical abundances)

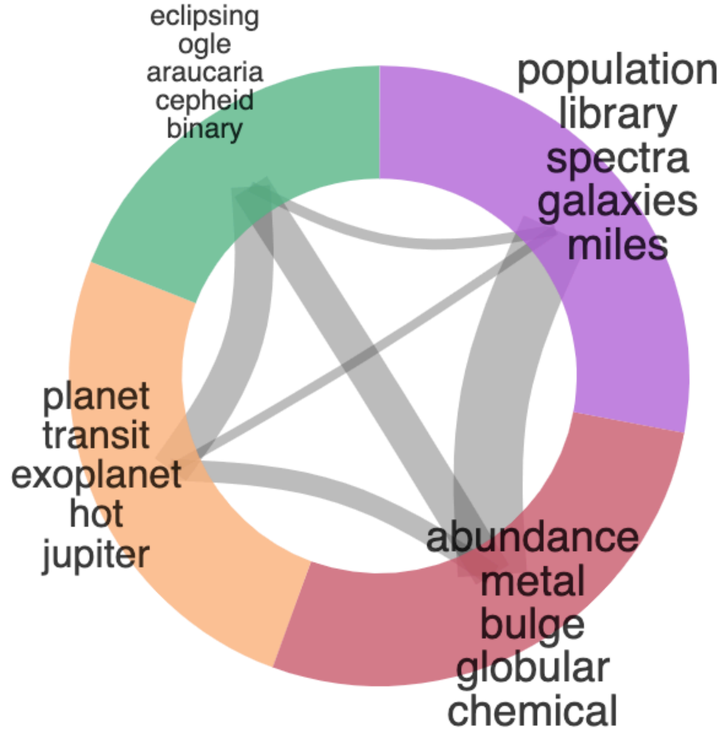
It can be primarily classified as:

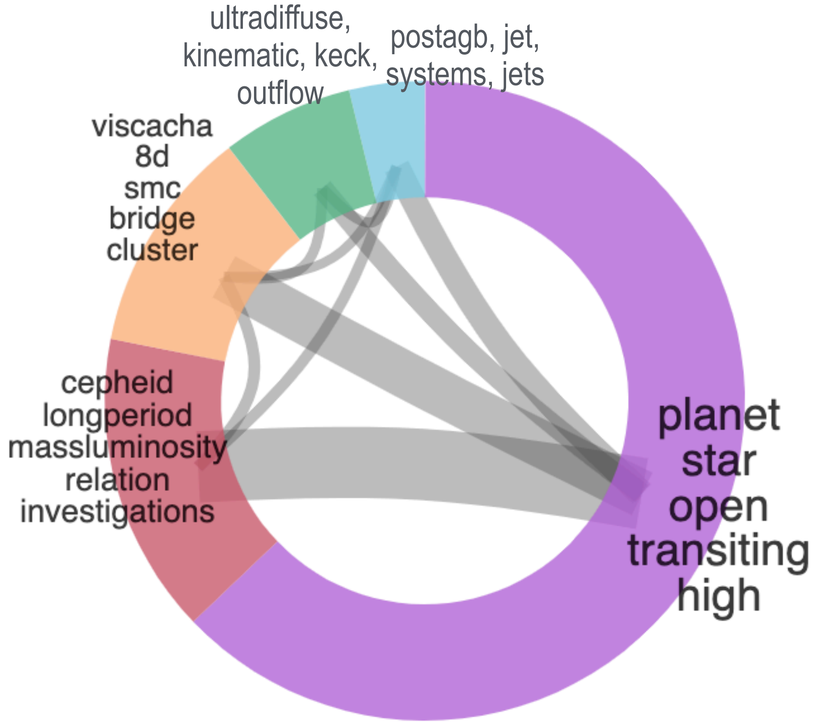
- An empirical library: a collection of observed spectra or
- A theoretical (synthetic) library: a collection of simulated spectra based on model atmospheres and radiative transfer codes

Why do we care for SSLs?

A sample of applications:

- atmospheric parameters in stars
- chemical abundances in stars and stellar clusters
- exoplanets, transits
- variable stars, eclipsing binaries
- calibration of photometric surveys
- cosmic distance scale
- jets and mass accretion in post-AGB systems
- kinematics in ultra-diffuse galaxies
- outflows in AGNs
- *last but not least*, integrated stellar populations





ADS paper networks from citations to Coelho+05 and Coelho14.

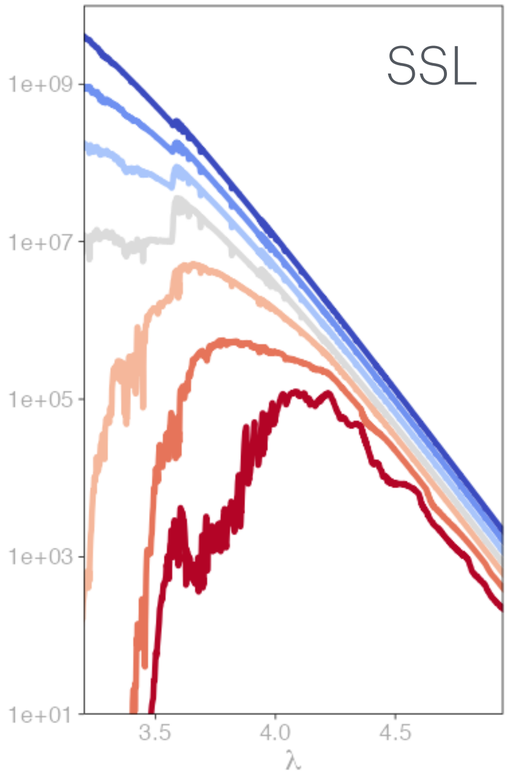
Why do we care for SSLs in StelPops?

The layer of observability in stellar population models

Isochrone Synthesis → IMF + Isochrones

Fuel Consumption Theorem → IMF + Isochrones in MS, fuel consumed in Post-MS

CMD Synthesis → Observed stellar CMDs

+ 

= Integrated StelPop Models

Past

How did stellar spectral libraries in astronomy evolve?

A systematic review of the literature*

Analysis question: How have stellar spectral libraries evolved through time?

Database	NASA ADS

Search strings	`title:(("stellar" OR "stars" OR "standard" OR "standards")`
	`AND ("spectral" OR "spectra" OR "spectrophotometric" OR "synthesis")`
	`AND ("library" OR "libraries" OR "atlas" OR "database" OR "grid"))`

Inclusion criteria	Astronomy ☆ Refereed ☆ Full text available in ADS
Exclusion criteria	about the codes ☆ about SSP models, isochrones or equivalent ☆ about an application of an SSL ☆ characterisation (e.g. atmospheric parameters) ☆ spectra of galaxies ☆ relative to only one star

* Guidelines from Kitchenham & Charters (2007) and M. Coelho (2023)

Created from the titles with wordart.com

- ~190 references gathered by the systematic review
- Plus manual additions from ADS Citation Helper (FoF), the list maintained by David Montes, Spanish VO list, and compilations in SSLs papers.

Thanks to David Montes and Letícia Laurindo for the help

Visit https://tinyurl.com/SSL-for-IAUS395

211 papers from 1899 to now

empirical	143 (74%)
synthetic	42 (22%)
hybrid	8 (4.1%)

General purpose	79 (41%)
Warm and cool stars	26 (14%)
Hot stars	19 (9.9%)
Cool stars	12 (6.3%)
Wolf-Rayet stars	11 (5.7%)
Young stellar objects	7 (3.6%)

+ brown dwarfs, carbon ☆, variable ☆, white dwarfs, symbiotic ☆, emission-line ☆, magnetic ☆, multiple populations in GCs, post-MS, subdwarfs.

The first libraries

A Historical Mention

- 1899MNRAS..59..217 - Gold Medal presented to Mr. Frank McClean for his photographic survey of star spectra in both hemispheres
- Photographs of stellar spectra λλ330 — 487nm
  - 1900MNRAS..60..392 - Council note on Sir W. and Lady Huggins's atlas of representative stellar spectra
  - 1900ApJ....12..291H - REVIEW: an Atlas of Representative Stellar Spectra by Sir William and Lady Huggins
  - 1900PASP...12..246C - "An Atlas of Representative Stellar Spectra." A Review

The Gold Medal.

The Council have awarded the Society's Gold Medal to Mr. Frank McClean, for his photographic survey of star spectra in both hemispheres, and other contributions to the advancement of astronomy.

The Library.

A supplementary catalogue, containing the additions to the library from 1884 June to 1898 June, is in preparation and will shortly be published.

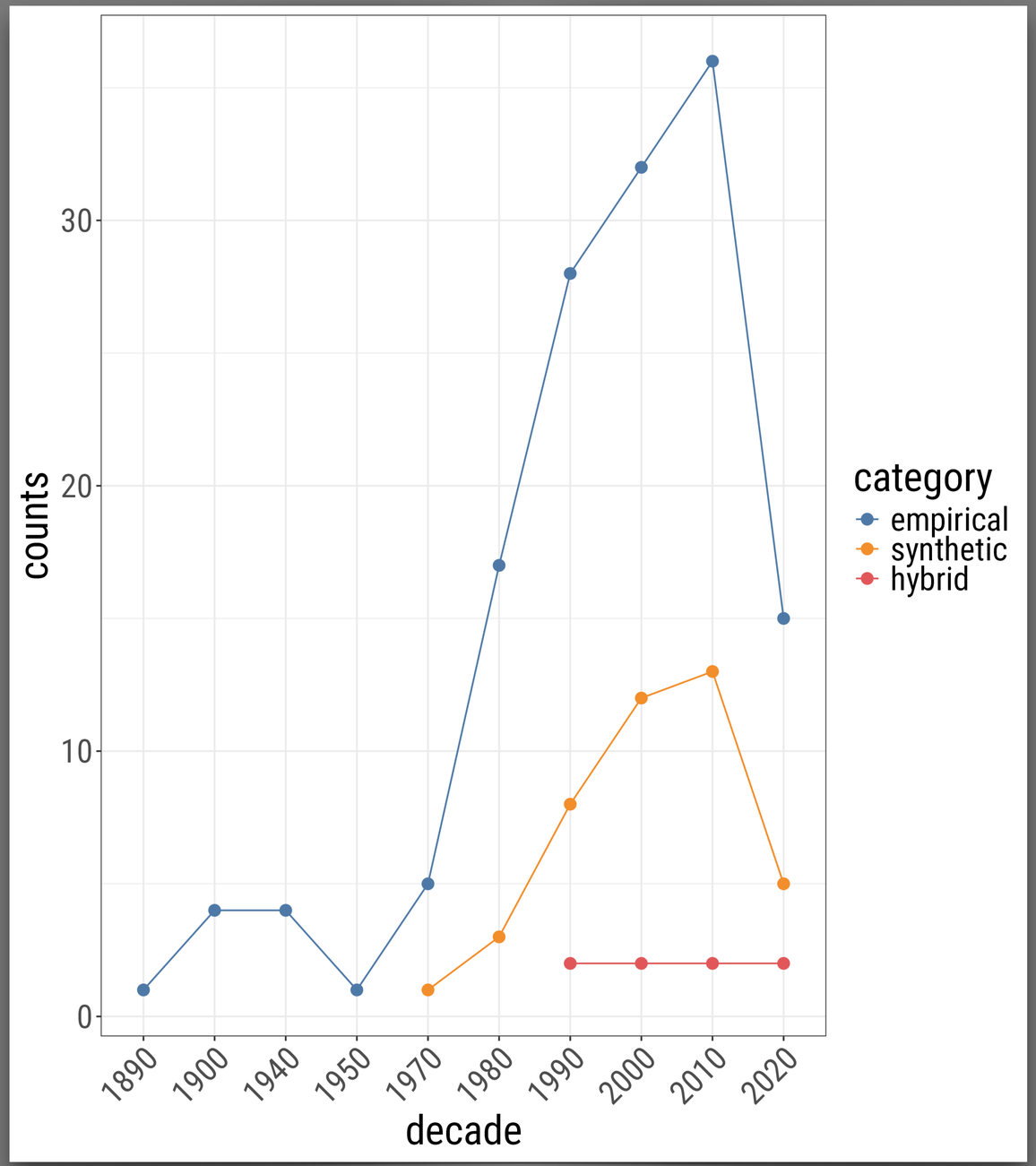
S

Sir William and Lady Huggins's Atlas of Representative Spectra.

In the striking volume which has just appeared, published in such tasteful form as to recall some ancient volume rather than a modern scientific work, Sir William and Lady Huggins set forth an account of pioneering research in astrophysics. The volume contains a remarkable series of plates reproduced from photographs of stellar spectra between the wave-lengths 4870 and 3300. This series has doubtless determined the title of the volume, but the plates are accompanied by 165 pages of text, which contain much new and important matter, dealing, as the title-page indicates, with the "evolutional order of the stars and the interpretation of their spectra."

Number evolution of SSLs

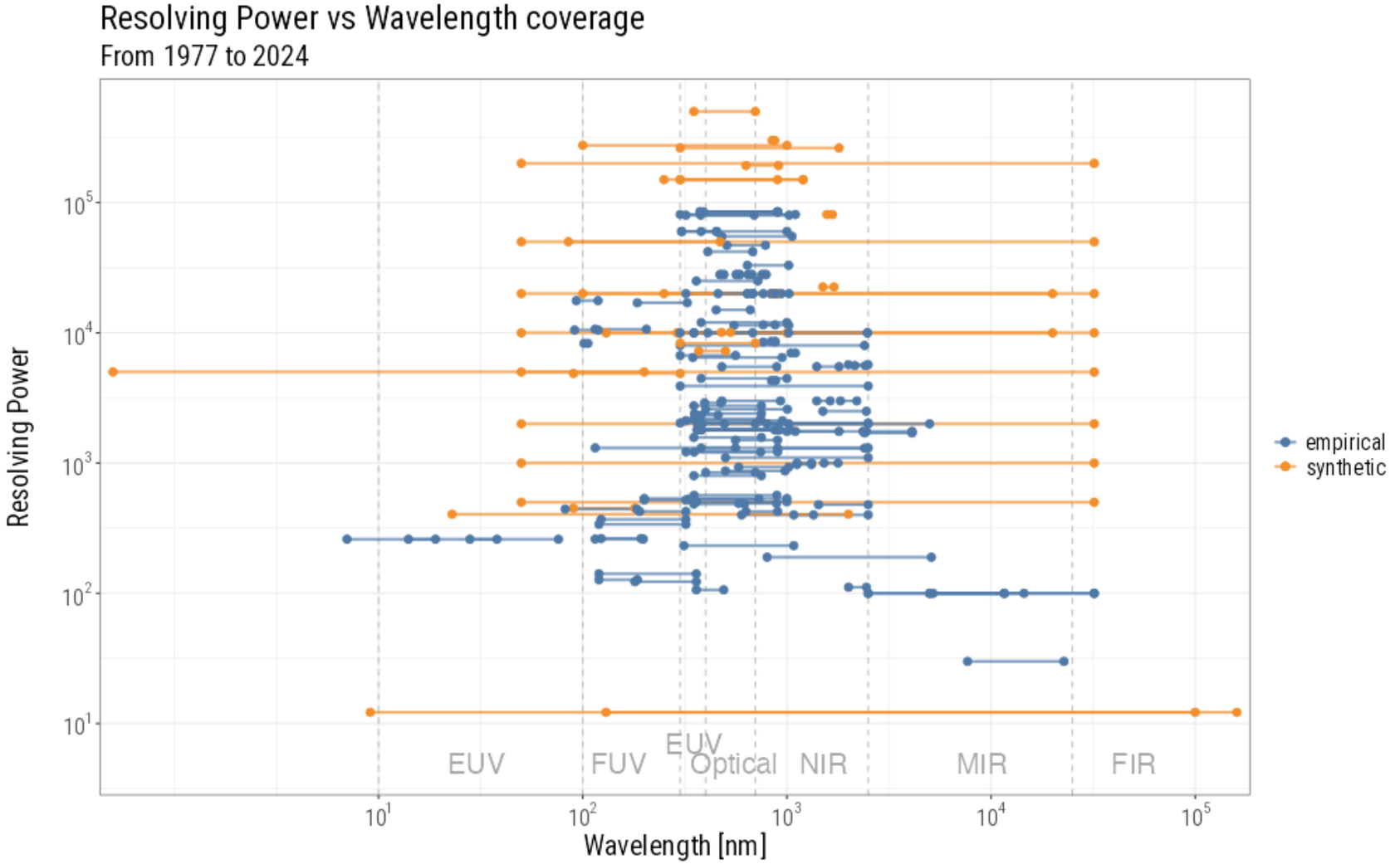
- The use of Charge-Coupled Devices (CCDs) began being used in Astronomy in the mid-1970s
- Beatrice Tinsley publishes her work on evolutionary synthesis in a series of papers in the 70s (Tinsley 1968, 1974, 1978, 1979, 1980 and Tinsley & Gunn 1974 - thanks to Claus Leitherer for pointing it out).



Coverage in R *vs* λ space

Evolution with time

- The first references with well-defined resolution and coverage date back to 70's
- *An atlas of stellar spectra. I.*, (Johnson 1977) - observed with a spectrophotometer with silicon photodiodes
- *Model atmospheres for G, F, A, B, and O stars* (Kurucz 1979)



Beatriz's contribution

Using synthetic spectra to go beyond the chemistry of the solar neighbourhood

In the 90s...

- **Observational context:** Peletier89 and Worthey+92 highlight a significant limitation of empirical libraries - their inability to represent integrated light of elliptical galaxies

- **From model studies:** Using PFANT (Spite67, Barbuy82; see also Cayrel+91), Barbuy+92 investigate the magnesium indices as a function of stellar parameters. Barbuy94 uses these models to compute integrated spectra of globular clusters (λλ490-540 nm).

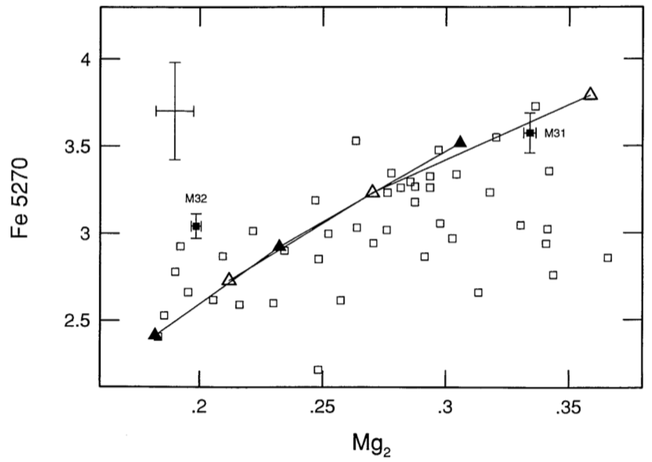


FIG. 2.—Fe line strengths, corrected for velocity broadening, of the best-observed IDS elliptical nuclei vs. Mg_2, from Table 1. Scatter is real and residuals from the mean relations are correlated between (*a*) and (*b*). The smaller errors of M32 and M31 are shown, along with an approximate maximum 1 σ error bar. Model predictions for ages 9 (*solid*) and 18 Gyr (*open*) are superposed. Symbols appear at [Fe/H] = −0.25, 0.0, and +0.25. No combination of age and metallicity can account for the shallow slope of the observations.

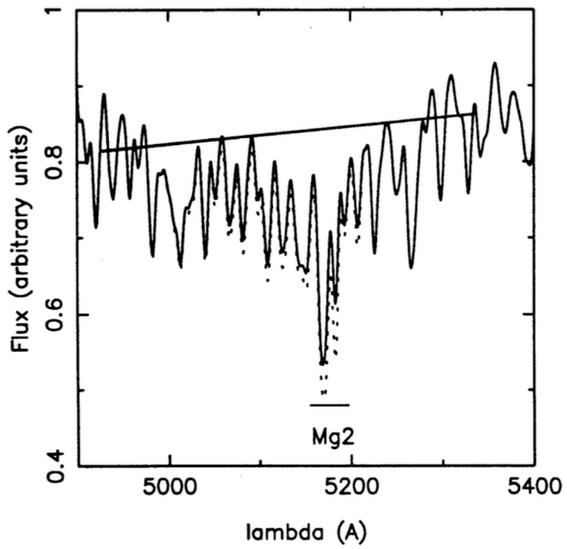


FIG. 1.—Synthetic composite spectrum for [Fe/H] = 0.0, [Mg/Fe] = 0.0 (*solid line*) and +0.25 (*dotted line*) convolved with a FWHM = 6.0 Å Gaussian. The Mg_2 bandpass and the continua adopted are indicated.

Beatriz's contribution

In the 2000s...

- **Synthetic SSLs:** Barbuy+03 presented a synthetic SSL designed to study the impact of α-enhancement on λλ460–560 nm. The grid evolves to Coelho+05, a library of high-resolution synthetic spectra covering λλ300nm to 1.8μm and both solar and α-enhanced compositions.

- The development of the first SSP models at high spectral resolution considering α-enhancement in both stellar spectra and isochrones in Coelho+07.

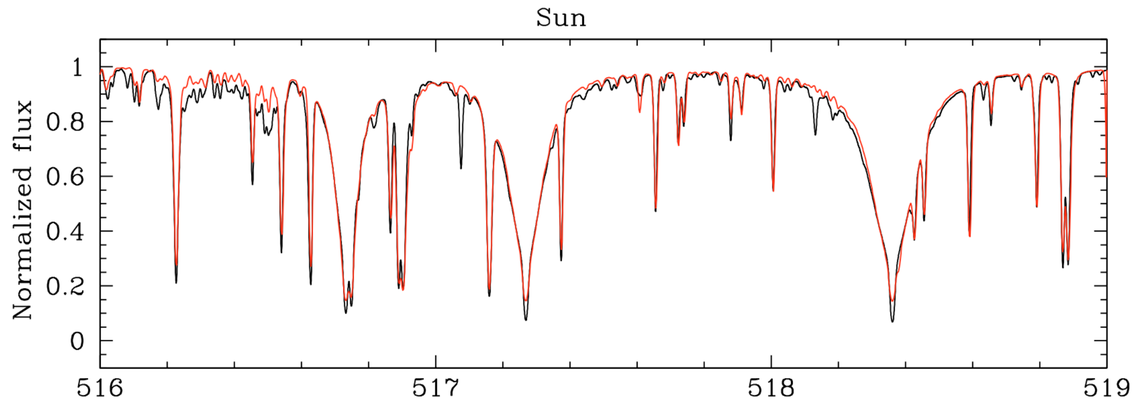


Fig. 1. *Upper panel*: comparison of the observed solar spectrum (thin line) and synthetic spectrum (thick line). *Lower panel*: comparison of

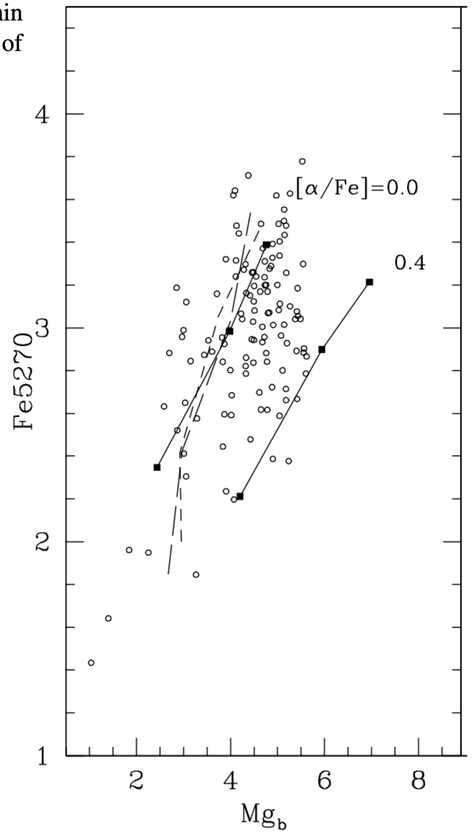


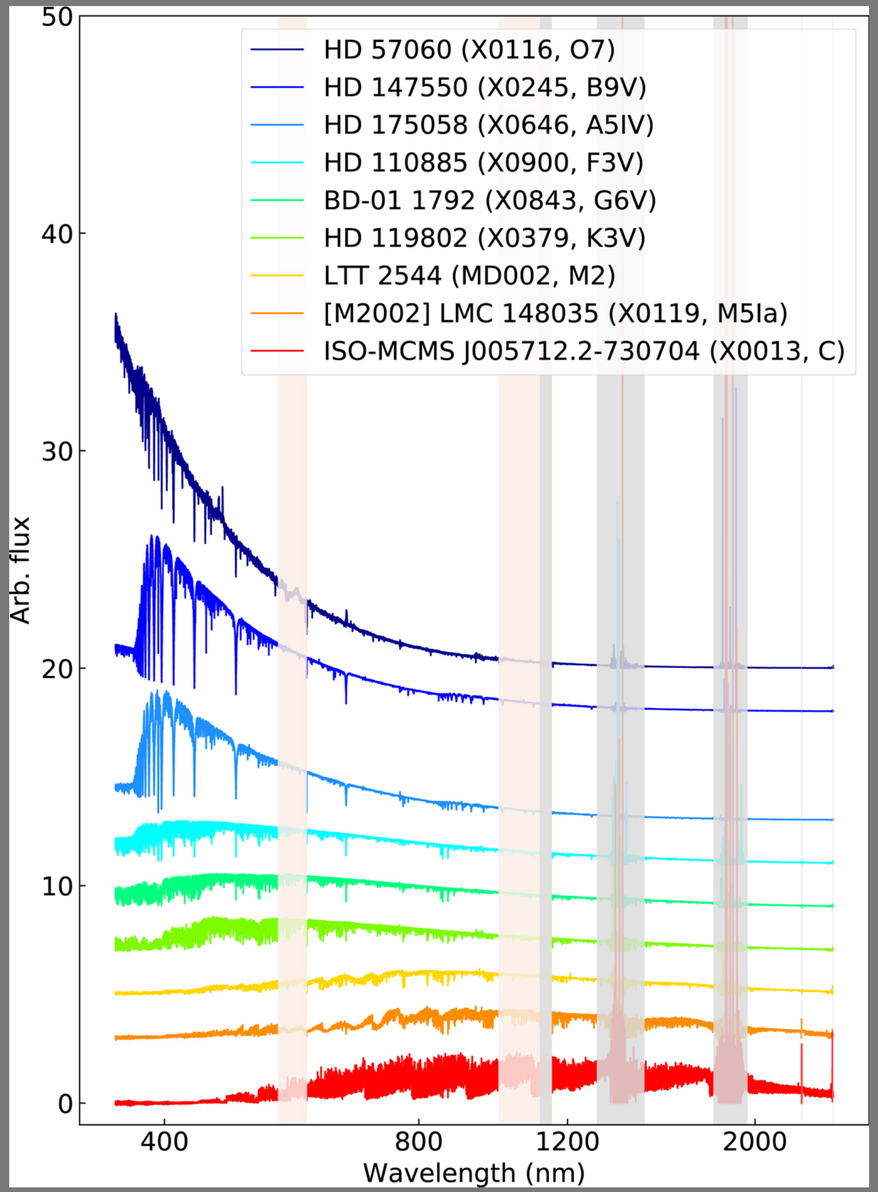
Figure 14. SSP models at constant age of 12 Gyr are plotted with the galaxy data from Trager et al. (1998). Left-hand panel: Solid lines show models by the present work, where the solid squares indicate [Fe/H] = −0.5, 0.0 and 0.2 (the most metal-rich systems have higher index values). Short-dashed lines indicate BC03 models, and long-dashed lines are CB07 Indo-US models. Right-hand panel: The solid line is the same as in the left-hand panel. Short-dashed lines are

Present

What is the state-of-the-art of stellar spectral libraries in astronomy today?

Empirical libraries

- X-Shooter Library (Chen+14, Gonneau+20, Verro+22) λλ350-2480nm, R ~ 10 000, 830 spectra of 683☆
- XShootU: Massive stars at low metallicity (Sana+24), 235 OB and Wolf-Rayet ☆
- Recalibrated UVES-POP (Borisov+23) λλ320 — 1025 nm, R ~ 20k and 80k (!!!), 406☆

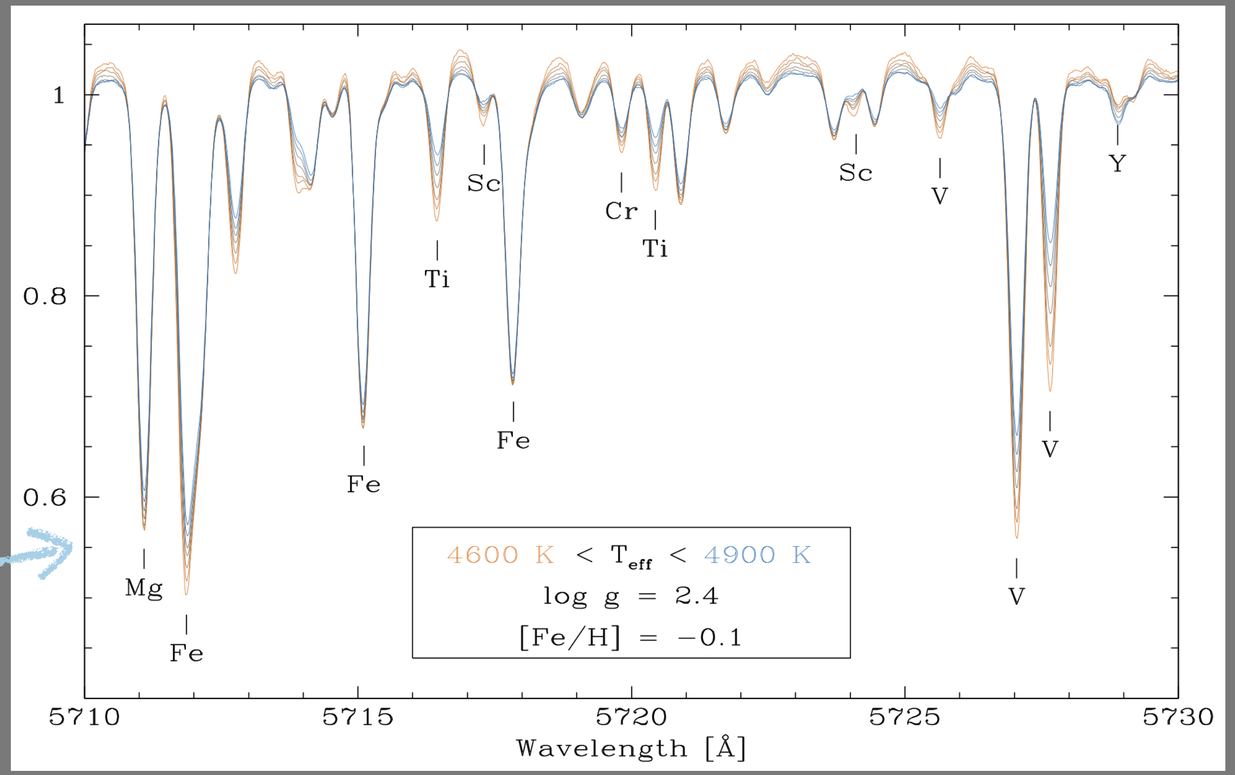


Typical XSL spectra in the OBAFGKMC sequence. Shaded bands mask the regions of dichroic contamination and deepest telluric regions in the NIR arms. Credit: Verro+22.

10^2 *vs* 10^6 stellar spectra ?

Making sense of the large number of stellar spectra available now

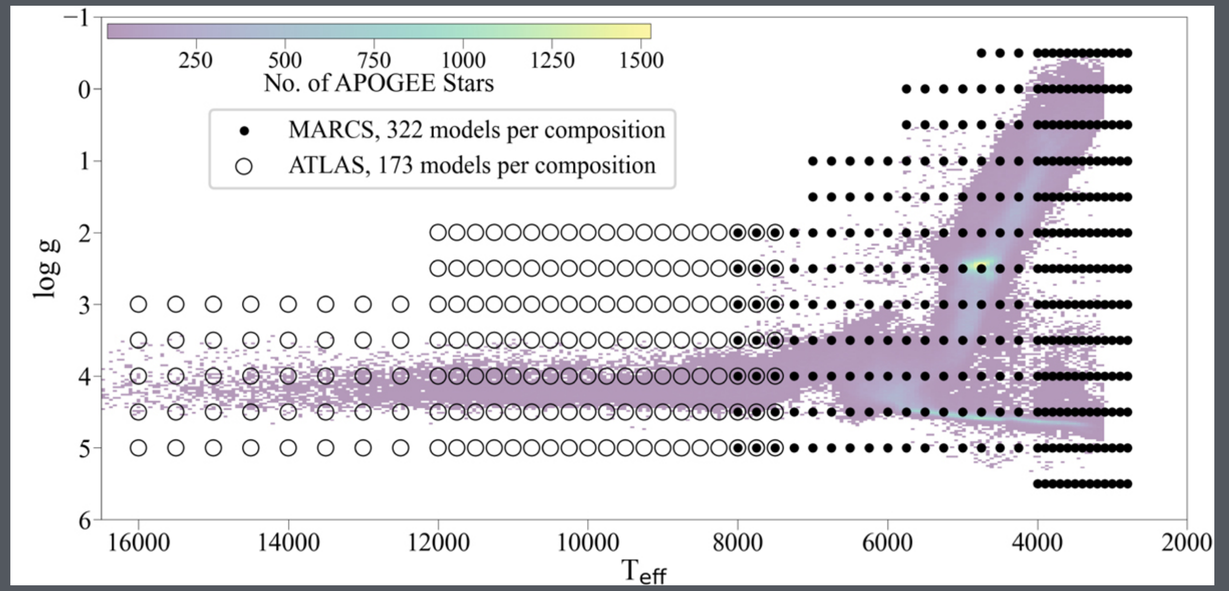
- SDSS-BOSS contains over 500k well-calibrated stellar spectra. LAMOST has ~8 million (DESI 16M?)
- Wei+14 (LAMOST), Kesseli+17 (SDSS-BOSS), and Zwitter+18 (GALAH+) provide libraries of “averaged” spectra grouped in different manners.
- "Virtually Noise-Free”: “Uncertainties are adequate for studies of dynamics *within* stellar clusters, associations, and streams in the Galaxy."
- Robust observational benchmark for evaluating and refining synthetic SSLs.



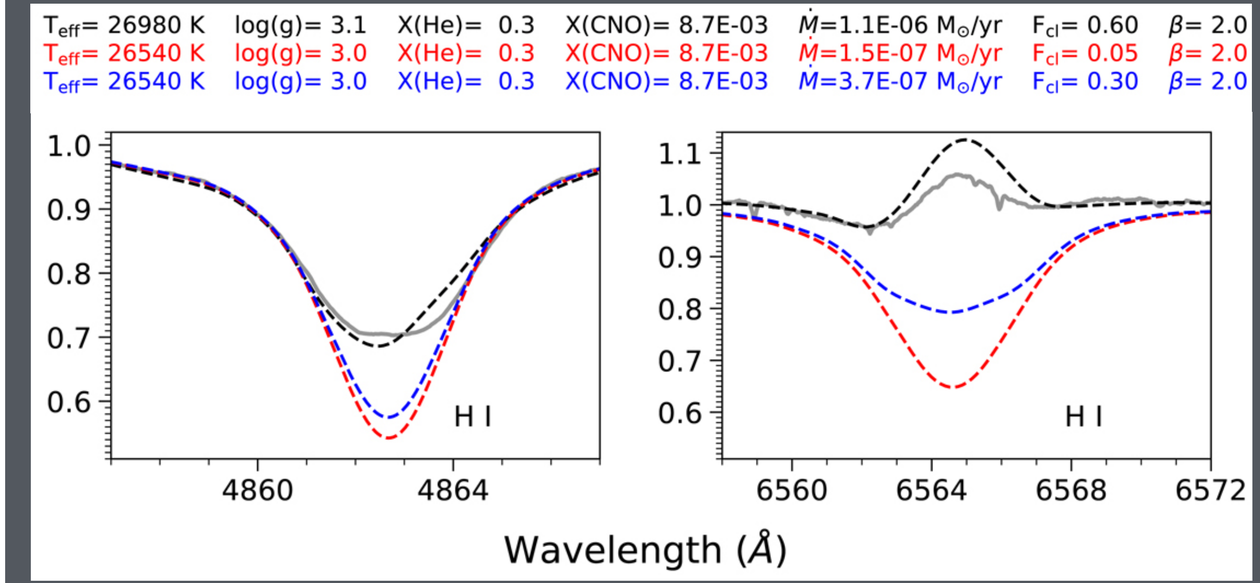
A sequence of observed averaged spectra which look like synthetic ones (“noise-free”). Credit: Zwitter+18.

Synthetic libraries

- The updated BOSZ library, Mészáros+24:
  - 628k spectra from 50nm — 32μm,
  - eight different resolutions from R = 500 to 50 000,
  - [M/H] from −2.5 to 0.75 dex,
  - [α/M] from −0.25 to 0.5 dex,
  - [C/M] from −0.75 to 0.5 dex
- OB main-sequence and Wolf-Rayet stars computed with CFMGEN, Zsargó+20:
  - ~80k models,
  - UV (90–200nm), optical (350 – 700nm), NIR (1 – 4μm)
- Check the compilation at the Spanish VO website and the POLLUX database



The parameter space covered by the new BOSZ grid. Credit: Mészáros+24.



Comparison of best-fitting models with the observed H I lines for ϵ Ori (solid gray line). Credit: Zsargó+20.

The *clash* between empirical *vs* theoretical libs

In integrated stellar populations models

- Traditionally,
  - empirical libs have been preferred in intermediate-age and old populations and
  - synthetic libs have been preferred in young populations.
- There are ways of combining them:
  - BaSeL (Lejeune+97, 98, Westera+02)
  - Stritzinger+05, Mironov+14, Schmidt+14, Knowles+21, Cai+24

- But for the sake of argument, let's keep them apart:
  - Empirical bibs are better because the stars are real (even if I don't know how to tag them accurately)
  - Synthetic bibs are better because they have more predictive power (coverage of the parameter space)

Which had the most impact?

Total number of citations as a proxy for impact

1 ☐ 1979ApJS...40....1K 1979/05 cited: 3850

Model atmospheres for G, F, A, B, and O stars.

Kurucz, R. L.

2 ☐ 2008A&A...486..951G 2008/08 cited: 2242

A grid of MARCS model atmospheres for late-type stars. I. Methods and general properties

Gustafsson, B.; Edvardsson, B.; Eriksson, K. *and 3 more*

3 ☐ 2013A&A...553A...6H 2013/05 cited: 1343

A new extensive library of PHOENIX stellar atmospheres and synthetic spectra

Husser, T. -O.; Wende-von Berg, S.; Dreizler, S. *and 4 more*

Total number of citations of the SSL ADS Library: 32,628

Number of citations of the top 3: 7,435

4 ☐ 2006MNRAS.371..703S 2006/09 cited: 1305

Medium-resolution Isaac Newton Telescope library of empirical spectra

Sánchez-Blázquez, P.; Peletier, R. F.; Jiménez-Vicente, J. *and 6 more*

5 ☐ 1998PASP..110..863P 1998/07 cited: 1293

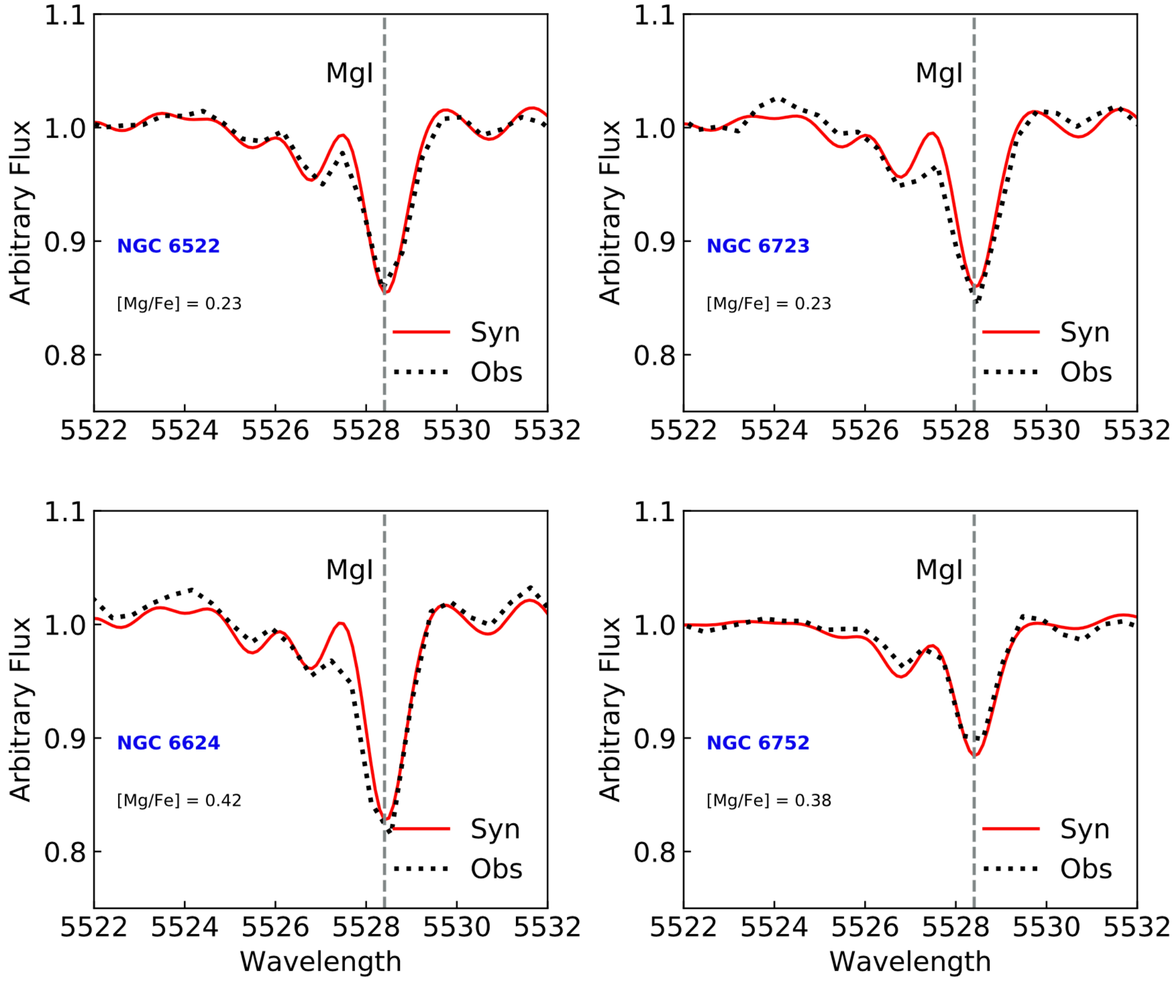
A Stellar Spectral Flux Library: 1150-25000 Å

Pickles, A. J.

The present performance of synthetic libraries

Measuring abundances in integrated light

- Moura+19 presents SynSSP, which uses synthetic stellar spectra to model integrated light of GCs.
- Rennó+20 used it to infer integrated abundances of Mg, Al, Si, Ca, Ti, Ba, and Eu in 47Tuc. The results are compatible with the values derived from stellar spectroscopy.

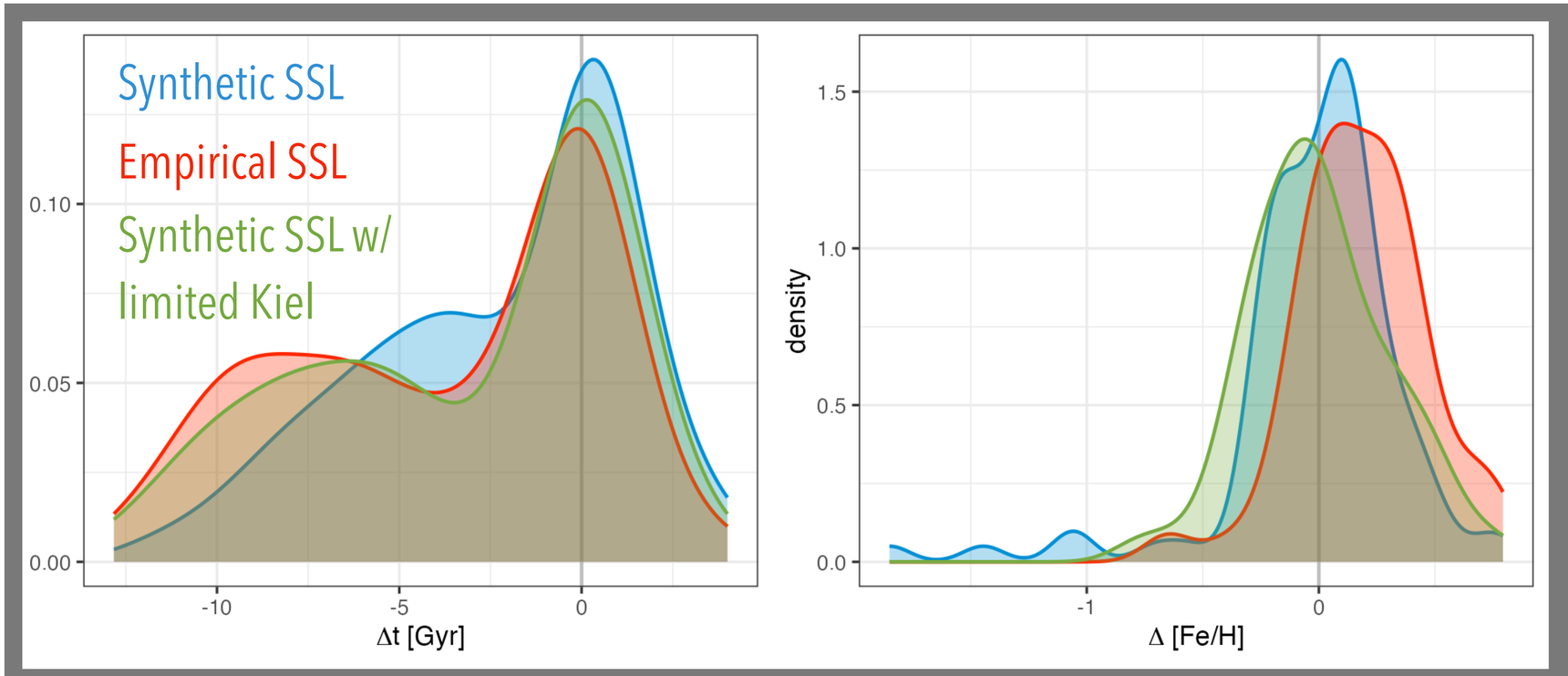


The observed and synthetic spectra for the Mg I line in 5528.405 Å, for different clusters. Credit: Moura+19.

The present performance of synthetic libraries

Measuring ages and iron abundances from spectral fitting

- Asa'd+(submitted) infers integrated ages and [Fe/H] from a sample of GCs (Usher+17, Spyropoulos+ SOAR). Spectral fitting with STARLIGHT, SSP models with either empirical or synthetic SSL. λλ370 – 540nm
- Synthetic SSL match the isochrone ages better (Δt = -1.9 *vs* -4.0 Gyr)
- Synthetic SSL match the highres [Fe/H] better (Δ[Fe/H] = +0.05 *vs* +0.20 dex)
- see as well Martins+19, Coelho, Bruzual & Charlot 20



Distribution of Δparameters (integrated - literature). Credit: Asa'd+ submitted.

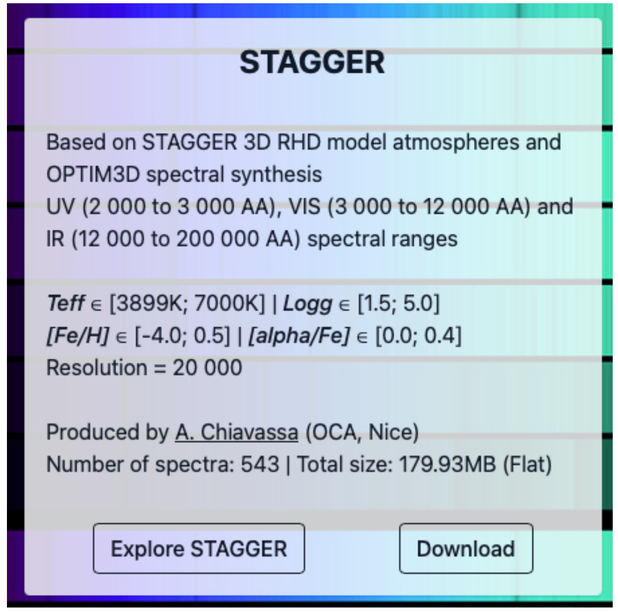
Future

What is ahead?

Next steps in synthetic libraries

Updates in the Physics and Opacities

- We are doing very well, in the optical.
- Sophisticated physics is a reality for hot stars
  - What about cool/warm?
    - The STAGGER-grid: A grid of 3D radiative hydrodynamical simulations, temporally averaged spectra (Chiavassa+18)



From POLLUX database

- Can we have better opacities, please?
  "The most sophisticated 3D MHD model will be wrong if the opacities are wrong."
  - There are ways to improve empirically (e.g. Cai+24 for a recent reference)
  - Yet working on the fundamental building blocks is unavoidable, e.g. *ASOS: International Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysical and Laboratory Plasmas* (14th Edition in Paris 2023)

How far can we reach with empirical libraries?

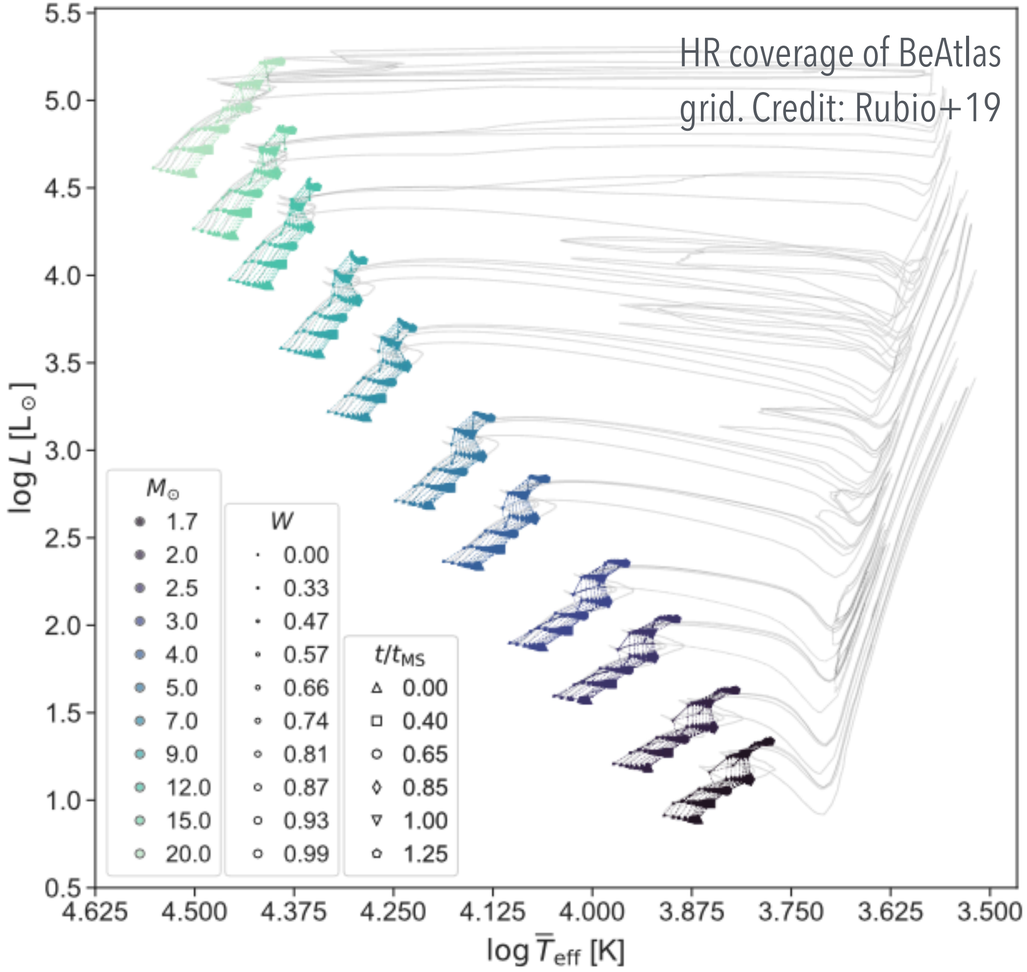
Resolved Stellar Populations beyond the Local Group

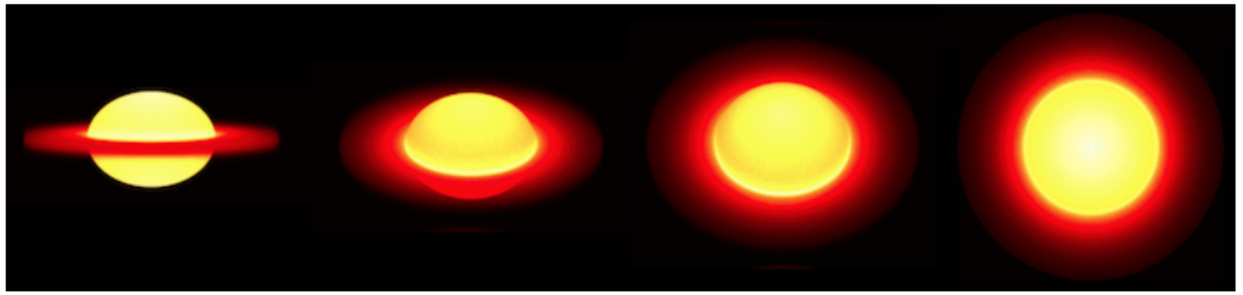
- With current facilities, detailed spectroscopic observations of individual stars are limited to the Milky Way and its nearest neighbours.
- MOSAIC (Evans+15):
  - Multi-object and multi-integral field spectrograph with large FoV
  - λλ 0.45 — 1.8 μm.
  - R ~ 4 000 and 18 000.

- Within the Local Group itself, MOSAIC will reach stars below the main sequence turn-off.
- Observations of red giant stars will be possible well beyond the Local Group, including galaxies in the Sculptor group (NGC 55, NGC 300).
- Tracers of young stellar populations (red and blue supergiants and super star clusters), will be observable at far greater distances, potentially out to 100 Mpc and beyond.

How to deal with Big Data?

- Rubio+23 presents "BeAtlas": B-type fast-rotating stars with circumstellar disks.
- Two grids of models: a purely photospheric (i.e. discless) grid, and a star + disc grid ('disc grid'). 616k synthetic spectra, 3D NLTE radiative transfer.
- Observables tailored to instruments:
  - cover from 100nm to Radio 4 GHz (75 000μm)
  - spectra, photometry and images
- Accompany a framework for Bayesian inference of atmospheric/disk parameters

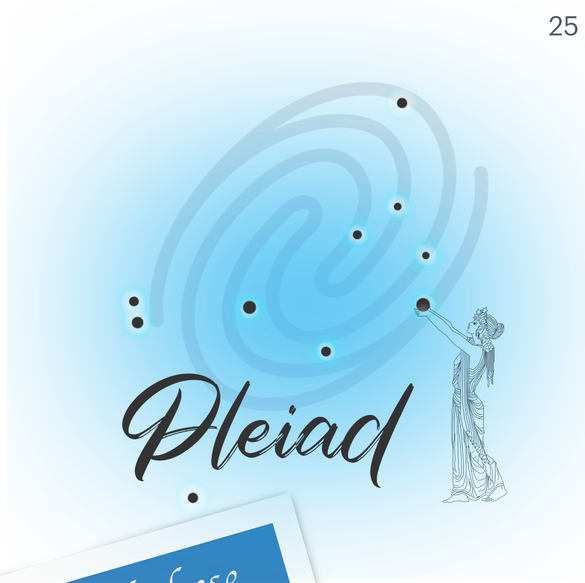




Hdust simulation of the Be star Achernar. Credit: B. Mota19, courtesy D. M. Faes.

Concluding remarks

- We came a long way https://tinyurl.com/SSL-for-IAUS395
- Synthetic SSLs will continue to dominate because of their predictive power.
- Empirical SSLs will always be the "grounding truths" that prevent the models from going nuts.
- Big Data is here - grids have increased in volume and complexity. How can we best offer them to the community?



If you like SSLs, go check these posters!

- P01 - Abel de Burgos
- P40 - Lucimara Martins
- P50 - Morgan Camargo
- P68 - Thayse Pacheco
- P73 - Vinicius Branco

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